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Annual Letter Report for 4/1/88-3/31/89

(1) Title: Fundamentals of Middle Atmospheric Dynamics.

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(2) Technical Objectives:

The middle atmosphere is a highly nonlinear dynamical system whose variability, and forecastability, is very poorly understood. We know for instance that the state of the mesosphere should be highly sensitive to the propagation of both gravity and Rossby waves from below, and that propagation can be sensitive to various kinds of wave-mean, wave-wave, and wave-turbulence interactions that occur on the way up. On longer timescales, there are trends in, for example, temperatures, chemical composition, and thresholds for aerosol and cloud formation, that may significantly change mean and extreme conditions in the middle atmosphere from year to year. These trends are partly a result of man-made perturbations and involve an intricate interplay of chemical, radiative and dynamical processes over a vast range of space and time scales, depending for example on the statistical properties of the wave-turbulence interactions. The problems thus posed are of formidable technical and conceptual difficulty. Progress is hindered by a lack of knowledge at the most fundamental level, particularly regarding the scale-interactive dynamical processes. The long-term aim of this project is the ambitious one of developing, testing and exploiting new theoretical concepts and modeling techniques to achieve a radically improved understanding of these processes.

(3) Approach:

The approach is first the maintenance and active development of a sophisticated numerical modelling capability, taking full advantage of our access to big supercomputing resources and collaboration within the UK Universities' Global Atmospheric Modelling Project (UGAMP), of which we are a member, second to continue our search for new theoretical concepts and to test them in a hierarchy of model experiments -- some at unprecedentedly high numerical resolution -- and third to develop new and ergonomically efficient ways for scientists to interact with numerical models and, ultimately, observational data. To this end we have installed and are exploiting modern workstation facilities. Innovation includes (a) new approaches to understanding wave, mean-flow interactions and wave-vortex interactions based on combining numerical modelling with abstract theories of Hamiltonian dynamics and on using and further developing the concept of "potential vorticity inversion", (b) development and exploitation of new numerical algorithms to study previously inaccessible scale interactions, and (c) studies of scale-sensitive interactions between dynamical processes on the one hand, and radiation and chemistry on the other.

(4) Accomplishments since 1 April 1988:

Dr Dritschel has continued to make important contributions to our understanding of ultra-fine-scale vortex interactions. His work is providing new insights into the behaviour of vortex structures in large-scale shear and strain, and now appears to be opening the way to a radically new approach to modelling and understanding the "layerwise-two-dimensional turbulence" that is believed with good reason to form the most significant motion in large portions of the middle atmosphere. Several different types of model have all been indicating that this (highly inhomogeneous) turbulence is the typical consequence of the "breaking" of planetary-scale Rossby waves that have propagated into the wintertime middle atmosphere from the troposphere below. The mixing produced by this Rossby-wave breaking is not quantitatively describable using conventional eddy diffusivity or flux-gradient concepts. One effect to which it does lead, however, is the formation of dynamical barriers against latitudinal chemical transport, such as the barrier that makes possible the formation of the Antarctic ozone hole.

One of the basic processes that has been studied is the behaviour of long vortical filaments subject to large-scale shear and strain. The numerical modelling repeatedly shows that this behaviour is of central importance to understanding layerwise-two-dimensional turbulence. Drs Dritschel, Haynes, Juckes and Shepherd have collaborated in a benchmark study of this problem, using a powerful combination of analytical and numerical techniques, that has greatly advanced our knowledge of it, and appears to account for much of the behaviour seen in our ultra-high resolution numerical simulations. A major publication is in a late stage of preparation.

Drs Haynes and Shepherd have discovered a fundamental error in the conventional theoretical formulation of the global atmospheric circulation problem in the presence of a lower boundary such as the Earth's surface. The resulting paper is to appear in the Quarterly Journal of the Royal Meteorological Society, probably early next year.

Dr McIntyre was seconded to the field phase of the NASA/NOAA Airborne Arctic Stratospheric Expedition (AASE) in Stavanger, Norway, where he acted as a theoretical adviser to the mission experimenters and flight planners, and spent time examing, and considering the implications of, the flight data. Contact with the research group in Cambridge was maintained regularly, and related numerical modelling studies initiated.

A collaboration has been initiated with members of Dr M.P. McCormick's Aerosol Research Branch at the NASA Langley Research Center. It appears that by combining our knowledge of fluid dynamics and our newly developed modelling capability with global-scale satellite observations of volcanic aerosol, we may be able to obtain new insight into the fundamental questions about the middle-atmospheric circulation and coupling mechanisms with which we are confronted. It appears that the satellite observations are revealing examples of barrier effects of the kind mentioned above, but in subtropical rather than subpolar latitudes. This in turn has far-reaching implications for the whole jigsaw puzzle of inhomogeneous wave-turbulence-radiative-chemical interactions.

Drs Haynes and Ward have been analyzing the scale-interactive effects of infrared radiative transfer upon fine-scale vortex structures. This is another fundamental problem that has to our knowledge never been addressed before. Preliminary results are indicating that radiative transfer usually limits the finest scale of potential-vorticity features before molecular diffusion does, but not by a great margin. This, then, slightly modifies the conclusions drawn by Juckes and McIntyre in their Nature Article of 1987, in the case of potential vorticity, but not in the case of chemical constituents.

Drs McIntyre and Norton have continued with their studies of potential vorticity inversion operators. These are now far better understood conceptually, and algorithmically have reached a degree of sophistication whose power and accuracy continues to surprise us, and to surprise colleagues to whom we show the results. We now believe we can explain the results by analogy with the Lighthill theory of aerodynamic sound generation. Dr Norton has just recently succeeded in finding how to make that analogy precise, by discovering the mathematical formalism that describes the appropriate generalization of the Lighthill theory. The generalized theory describes the spontaneous emission of inertia-gravity waves by vortical flows subject to Coriolis forces. We also now have the clear numerical examples of spontaneous wave emission and breakdown of high-order potential vorticity inversion that eluded us last year. These developments have opened the way (1) to quantitative assessment of the ultimate limitations of the potential vorticity inversion concept, and (2) to quantitative assessement of the spontaneous emission process and its possible impact on other aspects of the middle atmospheric circulation. A further spinoff is that this work has led to fresh insight into some old problems of wave, mean-flow interaction. One publication on these results is submitted, and another is in the late stages of preparation. A third should follow within the next year.

Dr Haynes has been developing new diagnostics for his high-resolution three-dimensional modelling effort. Model development has slowed with the realization that we may need to go to a special hybrid coordinate system in order to get the best possible results at ultra-high resolution. To avoid duplicating effort we have decided to await the outcome of work on such a system, to the design of which we have contributed but which is at present being worked on by other members of the UGAMP consortium.

Dr McIntyre has now completed his work on the mesospheric "turbulent Prandtl number" problem and on associated problems regarding the summer mesospheric circulation. This is a problem in which ingenuity in modelling is at a premium, since a direct attack will remain well beyond the reach of the largest supercomputers for many years to come. The results, which are due to appear shortly in the Journal of Geophysical Research (Special Noctilucent Cloud Issue, edited by Prof. Gary Thomas), give perhaps the clearest available demonstration of how drastically the effects of inhomogeneity in three-dimensional turbulence can change the estimates that one might make (and which have been proposed and widely used in the recent literature) on the basis of homogeneous turbulence theory.

Work on the man-machine interaction side of the numerical modelling effort is progressing well. A promising new, and highly interactive, way of viewing and modifying animated graphical output is undergoing testing and further development at present. This has excited considerable interest among visiting colleagues, and may well represent an advance in methods of interacting with numerical models that is ahead of the efforts of other research groups. Here we have been greatly helped by the expertise and versatility of the new programmer on the project, S.P. Cooper. Many of our insights into the spontaneous gravity-wave emission problem, for instance, were made possible by such graphical output.

(5) Significance:

We feel that the foregoing represents good progress toward our ultimate goal of an entirely new level of understanding of the complex "wave-turbulence jigsaw puzzle" that our work, and that of others, has already shown to be central to the nature of middle-atmospheric dynamics. The development of this understanding will be part and parcel of the development of a new and illuminating set of diagnostic techniques, and interactive facilities, for probing dynamical processes in high-resolution numerical models and in real observational data. The ultimate payoff is expected to be the development of a radically new generation of models and modelling techniques. These should significantly enhance our ability to describe, quantify and predict the multifaceted interactions between dynamical, radiative and chemical processes that characterize the behaviour of the middle atmosphere, and to be ready to exploit the unprecedentedly rich set of observational data that is expected to become available in the 1990s.

(6) Future efforts:

Some of these have already been indicated. We hope to push the three-dimensional modelling further using the new model mentioned above, and to continue to develop new diagnostics and modes of interaction using the workstations. We are now planning to put a special effort into modelling aspects of the circulation that bear on the Antarctic ozone-hole problem and the associated seasonal and interannual preconditioning. This promises advances on many fronts besides learning more about the ozone hole phenomenon itself. We have had many interesting discussions with colleagues in the Chemistry Department and at the British Antarctic Survey on these probl[illegible], and a collaboration is being set up involving several group membe[illegible]

In particular, Drs Haynes, Norton and Ward plan to tackle the difficult but extremely critical problem of quantifying -- at least in a high-resolution model context, but hopefully then for the real atmosphere -- the permeability of dynamical potential-vorticity barriers such as the edge of the polar vortex in the presence of radiative heat transfer. This is one typical example of a problem that requires new diagnostics to be developed; conventional Eulerian means hopelessly blur the essential effects. The problem is intimately related to the abovementioned problem of minmimum scale of potential-vorticity features.

Dr Haynes is planning to test his ideas on the downward control principle by developing isentropic-surface diagnostics for three-dimensional models, both those developed locally and those at present under development in other groups involved in UGAMP. Among other things, this gives an alternative view of the vortex permeability problem.

Two graduate students, Mr D.W. Waugh and Mr P.D. Clark, will be working respectively on non-standard Hamiltonian single-layer vortex models, and on fundamental mechanisms of internal variability of the middle atmosphere including the possibility of Rossby-wave resonance, concerning which there are new observational clues from the Antarctic.

A new postdoctoral researcher, Dr Gilbert Brunet, will be arriving this fall and will work on sophisticated wave-mean and related diagnostics and their application to the ultra-high resolution single-layer models.

Dr Dritschel plans to pursue his ultra-high resolution work, and to make a first attempt to construct and diagnose the simplest members of a radically new generation of layerwise-two-dimensional turbulence models.

Dr Norton, besides his involvement in the forthcoming collaboration on the Antarctic problem, also hopes to carry out quantitative tests of the generalization of the Lighthill theory that he recently discovered. This could have far-reaching implications; it should not only enable us to assess the theory's predictive power in estimating the strength and character of the spontaneous emission of inertia-gravity waves, but also to help quantify the limitations of the potential vorticity inversion concept.

We plan, of course, to remain fully and actively involved in UGAMP, participation in which gives us access not only to the aspects of modelling expertise in which other UK groups specialize, but also to the large supercomputer resources that are essential to this kind of work.

(7) (a) Publications:

Dritschel, D.G., 1988: Nonlinear stability bounds for inviscid, two-dimensional, parallel or circular flows with monotonic vorticity, and the analogous three-dimensional quasi-geostrophic flows. J. Fluid Mech. 191, 575-582.

Dritschel, D.G., 1988: The repeated filamentation of two-dimensional vorticity interfaces. J. Fluid Mech. 194, 511-547.

Dritschel, D.G., 1988: Contour surgery: a topological reconnection scheme for extended integrations using contour dynamics. J. Comput. Phys. 77, 240-266.

Dritschel, D.G., 1988: Contour dynamics/surgery on the sphere. J. Comput. Phys. 79, 477-483.

Dritschel, D.G., 1989: Contour dynamics and contour surgery: numerical algorithms for extended, high-resolution modelling of vortex dynamics in two-dimensional, inviscid, incompressible flows. Computer Phys. Rep., 10, 77-146.

Dritschel, D.G., 1989: On the stabilization of a two-dimensional vortex strip by adverse shear. J. Fluid Mech., 206, 193-221.

Dritschel, D.G., 1989: The stability of elliptical vortices in an external straining flow. J. Fluid Mech., in press.

Dritschel, D.G., and Legras, B., 1988: On the structure of isolated, coherent vortices in a two-dimensional, incompressible fluid at very high Reynolds numbers. J. Fluid Mech., in preparation.

Dritschel, D.G., and Legras, B., 1989: The stripping of isolated vortices by weak strain or shear forcing. J. Fluid Mech., in preparation.

Dritschel, D.G., Juckes, M.N., Haynes, P.H., and Shepherd T.G., 1989: The stability of a two-dimensional vorticity filament subjected to strain. J. Fluid Mech., to be submitted.

Dritschel, D.G., and McIntyre, M.E., 1989: Does contour dynamics go singular? Phys. Fluids A., submitted.

Haynes, P.H., 1988: The effect of barotropic instability on the nonlinear evolution of a Rossby-wave critical layer. J. Fluid Mech., in press.

Haynes, P.H., 1988: Forced, dissipative generalizations of finite-amplitude wave-activity conservation relations for zonal and non-zonal basic flows. J. Atmos. Sci., 45, 2352-2362.

Haynes, P.H. and Shepherd, T.G., 1988: The importance of surface-pressure changes in the response of the atmosphere to zonally-symmetric thermal and mechanical forcing. Quart. J. Roy. Met. Soc., in press.

Haynes, P.H., Marks, C.J., McIntyre, M.E., Shepherd, T.G., and Shine, K.P., 1989: On the downward control principle for extratropical diabatic circulations. J. Atmos. Sci., submitted.

Haynes, P.H., and Norton, W.A., 1989: Two and three dimensional simulations of stratospheric polar vortex dynamics. In preparation.

Juckes, M.N., 1988: A shallow water model of the winter stratosphere. J. Atmos. Sci., in press.

Juckes, M.N., and O'Neill, A., 1988: Early winter in the northern stratosphere. Q. J. Roy. Met. Soc., 114, 1111-1126.

Juckes, M.N., McIntyre, M.E., and Norton, W.A., 1988: High-resolution barotropic simulations of breaking planetary waves and polar-vortex edge formation. Q.J.Roy.Meteorol.Soc., to be submitted, September 1989.

McIntyre, M.E., 1988: A note on the divergence effect and the Lagrangian-mean surface elevation in periodic water waves. J.Fluid Mech, 189, 235-242.

McIntyre, M.E., 1989: On the Antarctic ozone hole. J. Atmos. Terrest. Phys., 51, 29-43. (Invited paper for IUGG Symposium special issue.)

McIntyre, M.E., 1989: On dynamics and transport near the polar mesopause in summer. J.Geophys. Res., special NLC issue, in press.

McIntyre, M.E., 1989: Does the concept of eddy diffusivity make sense in the (middle) atmosphere? Invited review for Middle Atmosphere Sciences Symposium, IAMAP 1989 Symposium held in Reading, UK, August 1988. IAMAP Extended Abstracts, available from Meteorology Dept, University of Reading, UK.

McIntyre, M.E., and Norton, W.A., 1989: Potential-vorticity inversion on a hemisphere. J. Atmos. Sci., to be submitted September 1989

McIntyre, M.E., and Norton, W.A., 1989: Dissipative wave-mean interactions and the transport of vorticity or potential vorticity. J. Fluid Mech. (G. K. Batchelor Festschrift Issue), submitted.

Shepherd, T.G., 1988: Nonlinear saturation of baroclinic instability. Part I: The two-layer model. J. Atmos. Sci., 45, 2014-2025.

Shepherd, T.G., 1988: Rigorous bounds on the nonlinear saturation of instabilities to parallel shear flows. J. Fluid Mech., 196, 291-322.

Shepherd, T.G., 1988: On Rossby waves modified by weak sinusoidal shear. Geophys. Astrophys. Fluid Dyn. 40, 225-237.

Shepherd, T.G., 1989: Nonlinear saturation of baroclinic instability. Part II: Continuously-stratified fluid. J. Atmos. Sci., 46, 888-907.

(b) Presentations:

By D.G. Dritschel:

Contour dynamics surgery. IMA deforming surfaces conference. Cambridge, England, December 1988.

The stabilization of a two-dimensional vortex strip by adverse shear. Euromech 245 background rotation conference. Cambridge, England, March 1989.

The stability of elliptical vortices in a straining flow. Geophysical Fluid Dynamics Seminar Series. DAMTP, Cambridge, England, April 1989.

The stability of elliptical vortices in a straining flow. Dynamical Systems Seminar Series. DAMTP, Cambridge, England, April 1989.

The stability of elliptical vortices in a straining flow. Mathematics Seminar Series. Imperial College, London, England, April 1989.

Two-dimensional vortex dynamics at extremely high Reynolds numbers. Mathematics Seminar Series. Bristol University, Bristol, England, April 1989.

The stability of elliptical vortices in a straining flow. Mathematics Seminar Series. University of Chicago, Chicago, USA, May 1989.

Vortex stripping. Mathematics Seminar Series. University of Chicago, Chicago, USA, May 1989.

Two-dimensional vortex dynamics at extremely high Reynolds numbers. Geophysical Fluid Dynamics Laboratory, Princeton, USA., June 1989.

The surviveability of vortices in a two-dimensional fluid at extremely high Reynolds numbers. IUTAM topological fluid dynamics conference. Cambridge, England, August 1989.

Filamentation: the mechanism inhibiting the development of large strain rates and singularities in a two-dimensional, inviscid, incompressible fluid with bounded vorticity. Fourth international workshop on nonlinear and turbulent processes in physics. Kiev, USSR, October 1989.

By P. H. Haynes:

Rossby-wave critical layers (2 lectures, University of Toronto).

The general circulation of the middle atmosphere (University of Toronto).

High-resolution 3 dimensional simulations of stratospheric flows (University of Toronto, Bedford Institute of Oceanography, York University, (Toronto)). Mean Meridonal circulations (University of Toronto, Dalhousie University, University of Cambridge, University of Oxford).

High resolution simulations of wintertime stratospheric flows in shallow-water and primitive-equation models (Invited presentation to Amer. Meteorol. Soc., Seventh Conference on the Meteorology of the Middle Atmosphere, San Francisco, April 1989.

High resolution simulations of stratospheric flows in a primitive-equation model. Middle Atmosphere Sciences Symposium, IAMAP 1989 Symposium held in Reading, UK.

By M.E. McIntyre:

Polar vortex dynamics. Polar Ozone Workshop, held at Snowmass, Colo. May 1988.

Contributions to planning meeting for the Airborne Arctic Stratospheric Expedition. NASA Ames Research Center, July 1988.

Transport and diabatic descent in a polar vortex. Invited seminar, NASA Ames Research Center. August 1988.

Air. Ten invited lectures to the Summer School on Nonlinearities in Geophysics, "Earth, Air, Fire and Water", held at UCLA, August 1988.

On the downward control principle for extratropical diabatic circulations. Invited seminar, NOAA Aeronomy Lab., Boulder, Colo., August 1988.

On the general circulation of the middle atmosphere. Seminar at Pennsylvania State University, August 1988.

The wave-turbulence jigsaw puzzle. Invited Seminar at DAMTP, Cambridge, UK, April 1989.

The Airborne Arctic Stratospheric Expedition. Invited lecture to the One Day Conference on the Environment, Cambridge, UK, April 1989.

On the downward control principle for extratropical diabatic circulations. Amer. Meteorol. Soc., Seventh Conference on the Meteorology of the Middle Atmosphere, San Francisco, April 1989.

The middle atmosphere: current challenges to our understanding. Invited review, Middle Atmosphere in the Southern Hemisphere, Lone Mountain Conference Center, San Francisco, April 1989.

Large scale transport processes in the stratosphere and troposphere. Invited paper for Middle Atmosphere Sciences Symposium, IAMAP 1989 Symposium held in Reading, UK, August 1988.

Does the concept of eddy diffusivity make sense in the (middle) atmosphere? Invited review for Middle Atmosphere Sciences Symposium, IAMAP 1989 Symposium held in Reading, UK, August 1988.

By W.A. Norton:

Balance and Potential Vorticity Inversion. Space and Atmospheric Physics Group, Imperial College, London, November 1988.

Balance and Potential Vorticity Inversion. Atmospheric Physics Department, University of Oxford, November 1988.

Calculation of atmospheric fields from a potential vorticity distribution in a time-dependent model. Workshop on recent developments in numerical techniques relevant to numerical weather prediction, Dynamical Specialist Group at the Royal Meterological Society, ECMWF, January 1989.

Potential-vorticity inversion on a hemisphere. American Meterological Society Conference on Atmospheric and Oceanic Waves and Stability, San Francisco, April 1989.

Balance and the breakdown of balance in a shallow water equition model. DAMTP, University of Cambridge, June 1989.

Balance and potential vorticity inversion. Department of Meteorology, University of Reading, May 1989.

Potential-vorticity inversion on a hemisphere. IAMAP Synposium, Reading, U. K., August 1989.

By T.G. Shepherd:

Two-dimensional turbulence in the atmosphere. Department of Earth, Atmospheric and Planetary Sciences, York University, Canada, December 1988.

Symmetries, conservation laws, and Hamiltonian structure for fluid flow (5 lectures). Scripps Institution of Oceanography, UCSD, January-February 1989.

A new twist to the classical axisymmetric response problem:

implications for tran…ent eddy parameterization. American Meterological Society Conference on Atmospheric and Oceanic Waves and Stability, San Francisco, April 1989.

Rigorous bounds on the nonlinear saturation of barotropic and baroclinic instabilities. Laborative de Meteorologie Dynamique du CNRS, Paris, and IFREMER, Centre de Brest, France, June 1989.

The importance of surface-pressure changes in the response of the atmosphere to zonally-symmetric thermal and mechanical forcing. IAMAP Symposium, Reading, U. K., August 1989.

By W.E. Ward:

The Effect of Radiative Heat Transfer on Small-scale Potential-Vorticity Structures in the Stratosphere, April 11, 1989. Amer. Meteorol. Soc., Seventh Conference on the Meteorology of the Middle Atmosphere, San Francisco, April 1989.

(8) Scientific personnel involved in the project:

Dr M.E. McIntyre (PI, Reader in Atmospheric Dynamics)
Dr P.H. Haynes (Royal Society Research Fellow)
Dr D.G. Dritschel (Sci. Engg. Res. Council)
Dr W.A. Norton (Postdoctoral research assistant, ONR-supported)
Dr T.G. Shepherd (Nat. Environm. Res. Council and U.of Toronto)
Dr W.E. Ward (Canadian Sci. Engg. Res. Council)

Mr. S.P. Cooper (programmer, part ONR-supported)
Ms. J.M. Wilkins (programmer, part ONR-supported)

Mr P.D. Clark (graduate student, Nat. Envir. Res. Council stu'ship)
Mr D.W. Waugh (graduate student, Commonwealth Scholar)